PSEUDO-RANDOM SEQUENCE PADDING
IN AN OFDM MODULATION SYSTEM

Field of the Invention

5   This invention relates to electronic communication of messages, and more

particularly to communication of information for Internet, digital television, data

broadcasting and other wideband applications.

Background of the Invention

Transmission of Internet signals and of digital television (TV) signals poses

10   different but continuing challenges for each activity. Internet signal transmission

faces the problems of reliable broadcasting and multicasting of messages,

provision of mobility for signal transmitter and for recipient, and limitations on

information transfer rate ("speed"). Transmission of digital TV signals faces the

problems of providing an interactive system, providing point-to-point information

15   transfer capacity, and mobility of the recipient. The system should be efficient in

the sense that the payload or data portion of each transmitted frame is a large

fraction of the total frame. At the same time, the system should be able to identify,

and compensate for, varying characteristics of the transmission channel, including

but not limited to time delay associated with transmission of each frame.

20   What is needed is a system that provides timing recovery, carrier recovery

and estimation of channel characteristics associated with signal propagation in a

channel, and that also serves as a guard interval and as a frame synchronizer for

the transmitted signal.

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Summary of the Invention

The invention meets these needs by providing a pseudo-random or pseudo-noise (PN) sequence for each transmitted frame, where the PN sequence satisfy certain orthogonality and closure relations with respect to algebraic operations such as convolution, Boolean addition and position shift within a segment. A convolution signal is formed between a received signal (transmitted through a channel) and one or more of a selected sequence of the PN sequences. This convolution signal is analyzed to identify the beginning or end of a PN sequence, to identify time delay in the channel, and to permit timing recovery. A carrier frequency for the received signal can be recovered from the signal symbols (bit, nibbles, bytes, etc.) that make up the PN sequences, and synchronization of signal frames can be implemented. Characteristics of the transmission channel can be estimated from the time delays and associated phase shifts. A PN sequence can be positioned within a signal frame to serve as a guard interval for an orthogonal frequency, multiple carrier modulation ("OFDM") scheme. Taken together, these features allow demodulation of a transmitted signal within an OFDM scheme.

Brief Description of the Drawings

Figures 1A and 1B illustrate alternative formats for an OFDM frame sequence.

Figures 2A, 2B and 2C illustrate alternative formats for incorporating a PN sequence according to the invention.

Figure 3 illustrates a set of PN sequences that can be formed within a frame sync segment.

Figure 4 illustrates a representative transmitted signal.

Figures 5A and 5B illustrate non-overlapping components of an idealized sequence of signal frames.

Figures 6A and 6B illustrate the incremental effects of a representative multipath (dotted lines) on a sequence of modified frame sync segments.

Figure 7 is a flow chart of a procedure for practising the invention.

Figures 8 and 9 illustrate a transmitter system and a receiver system that can be used to practice the invention.

Description of Best Modes of the Invention

An OFDM format for a signal in first and second configurations is shown in Figures 1A and 1B. In the format of Figure 1A, a DFT (or FFT) block 11A is preceded by a cylic prefix segment 13A that serves as a guard interval for the DFT block. Use of a guard interval, or its equivalent, is required with an OFDM format, in order to account for the possible presence of multipath signals in a received signal. In the format of Figure 1B, a DFT block is followed by a zero-padding segment that also serves as a guard interval for the DFT block.

A pseudo-random or pseudo-noise (PN) sequence, a coded m-sequence of symbols, is usedl in an OFDM format. An m-sequence is a sequence of symbols, usually 0's and 1's, of a selected length that satisfies three requirements: (1) the number of symbols of different types (e.g., the number of 0's and the number of 1's) is "balanced", or approximately the same, over the set of such sequences; (2) the Boolean sum of any two m-sequences, and the result of end-around shifting of symbols in any m-sequence, is again an m-sequence; and (3) the convolution of two m-sequences, $MS(t;i)$ and $MS(t;j)$, satisfies an orthogonality condition:

$$MS(t+\Delta t;i)*MS(t;j) = \delta(\Delta t)\cdot\delta(i,j), \tag{1}$$

where $\delta(\Delta\tau)$ is a modified delta function $(\delta(\Delta\tau) = 0$ for $|\Delta\tau| > \Delta t1)$ and $\delta(i,j)$ is a

Kronecker delta (= 0 unless i = j). The Kronecker delta can be omitted if the m-sequence is independent of the index number i, or if the index numbers are known to satisfy i = j. The length of an m-sequence is most conveniently chosen to be $2^J - 1$, where J is a selected positive integer, such as J = 7, 8 or 9.

5   A subset of the set of all m-sequences, referred to as coded m-sequences and denoted PN(t;i) for an index number i, are of interest. A set of (coded) PN sequences may be generated using Walsh sequence coding or using a similar Haar sequence coding. Techniques for generating Walsh codes or Haar codes are discussed in T.J. Lynch, Data Compression, Van Nostrand, New York, 1985, pp. 79-85, and in V.J. Garg, K. Smolik and J.E. Wilkes, Applications of CDMA in Wireless/Personal Communications, Prentice Hall, Upper Saddle River, New Jersey, 1997, pp. 23-39. Other sets of PN sequences, satisfying Eq. (1), can be generated and used as well.

          A PN sequence is a Mth order m-sequence that can be implemented by a Fibonacci-type linear feedback shift register (LFSR) that is well known in the art. One suitable characteristic polynomial, associated with the LFSR and used for the choice M = 9, is

$$p(x;4;9) = 1 + x^4 + x^9. \tag{2}$$

An initial condition mask, applied to the LFSR, determines the initial condition

20   of, and thus the phase of, a PN sequence that is generated. Any other suitable characteristic polynomial can be used here, consistent with the choice of order M.

          In a first embodiment, illustrated in Figure 2A, a coded PN sequence 23A is included in, or replaces, the cyclic prefix segment 13A shown in Figure 1A and is associated with the DFT block 21A. In a second embodiment, illustrated in Figure

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2B, a coded PN sequence 23B is included in, or replaces, the zero padding segment 13B shown in Figure 1B and is associated with the DFT block 21B.

In a third embodiment, illustrated in Figure 2C, a coded PN sequence 23C is associated with, and included in, a frame sync segment 25C that precedes and is associated with a DFT block 21C. The frame sync segment optionally includes a preamble 24C that immediately precedes the PN sequence 23C and optionally includes a post-amble 26C that immediately follows the PN sequence. The lengths of the preamble, the PN sequence and the post-amble are F1, F2 and F3, respectively, where F1 and F3 are selected non-negative integers and F2 is a selected positive integer. The frame sync segment has a length F1 + F2 + F3 symbols.

In the format shown in Figure 2C, the preamble and post-amble segments are not chosen arbitrarily. Preferably, the preamble and post-amble symbols are chosen so that any ordered set of F2 consecutive symbols from the frame sync segment (of length F1 + F2 + F3) is also a PN sequence; more particularly, a PN sequence formed by a selected number of end-around shifts of the "original" PN sequence located at positions number F1+1 through number F1+F2 in the frame sync segment, as illustrated in Figure 3. The frame sync segment, if present in the signal frame, may be characterized by an associated PN sequence (e.g., the "original" PN sequence indicated in Figure 3).

The information transfer unit used here is a signal frame, which includes the frame body 21A or 21B in the format shown in Figures 2A and 2B, or includes the frame sync segment 26C and the frame body 21C in the format shown in Figure 2C. The frame body, 21A or 21B or 21C, includes a DFT block with a header having a fixed number of signal symbols (octets, bytes, nibbles or bits) that

provide information on the frame source, frame destination, sequence number,

frame window size, if any, data type (supervisory, information, unnumbered), data

payload size, flow control, message priority, error detection and correction

checksum, and other supervisory information (referred to collectively as the

"header"), plus the data payload itself, which preferably has a fixed size, or may

have a prescribed range of sizes.

Let Tr(t) be a signal representing a sequence of transmitted signal frames,

as illustrated in Figure 4. A signal frame is identified by isolating and analyzing

an associated PN sequence, which requires precise knowledge of where each PN

sequence begins and ends within a sequence of signal frames.

A sequence of idealized modified signal frames can be decomposed into

two non-overlapping sequences: a first sequence S1 of PN sequences

PN(t;i;ideal), and a second sequence S2 of DFT blocks DFT(t;i;ideal), as

illustrated in Figures 5A and 5B.

However, each transmitted signal frame is subject to signal time delay,

including multipath signal degradation, and reasonably precise timing is required

in order to distinguish a PN sequence from any other segment within a signal

frame. Figures 6A and 6B illustrate the incremental effects of a representative

multipath signal mp(t) (dotted lines) on a sequence of modified frame sync

segments and on a sequence of modified DFT segments that are split apart as

illustrated. Although each idealized modified PN sequence PN(t;i;ideal) decreases

abruptly to 0 at t = t"(i), the received sequence PN(t;i;Rc) decreases to 0 slowly

within a time interval t"(i) $\leq$ t $\leq$ t'"(i) < t'(i+1), as illustrated in Figure 6A. In a

similar manner, although idealized DFT block DFT(t;i;ideal) decreases to 0

abruptly at t = t'(i+1), the received block DFT(t;i;Rc) decreases to 0 slowly within

a time interval t'(i+1) ≤ t ≤ t'''(i+1) < t''(i+1), as illustrated in Figure 6B. It is

thus difficult to locate the times, t = t'(i;Rc) and t = t''(i;Rc), at the receiver,

corresponding to the beginning and end of a PN sequence that would be received

without multipath.

Let h(t) be a response to transmission of an impulse signal δ(t) (modified

delta function with infinitesimal width Δt1) along the transmission channel TC

used for a signal frame. If the signal Tr(t) is transmitted along the channel TC, a

received signal Rc(t) may be expressed as a convolution of the transmitted signal

and the impulse response signal,

$$Rc(t2) = Tr(t1) * h(t2 - t1), \tag{3}$$

$$Tr(t) = PN(t;i;ideal) + mp(t)   (t'(i;Rc) \leq t < t'(i+1;Rc)), \tag{4}$$

where * indicates that a convolution or correlation operation is performed on the

two signals Tr(t1) and h(t2 - t1). Because of the orthogonal construction of each

PN sequence in Eq. (1), one verifies that

$$PN(t + \Delta t;i;ideal) * PN(t;j;ideal) = \delta(\Delta t) \delta(i,j) \tag{5}$$

$$PN(t + \Delta t;i;ideal) * Rc(t)$$

$$= \delta(\Delta t) * h(t) + (\text{small residual due to mp(t)}) \tag{6}$$

within a time interval t'(i;Rc) ≤ t ≤ t''(i;Rc), where the Kronecker delta index

δ(i,j) (= 0 or 1) can be dropped if the PN sequences PN(t;i;ideal) are independent

of the index i, or if the particular PN sequence (i) is known and i = j.

Where the sequence PN(t;i;ideal) is known and the impulse response h(t) is

measurable, and thus known, for the channel TC, the convolution signal formed in

Eq. (6) can be used to determine time points (t = t'(i;Rc) and t = t''(i;Rc))

corresponding to the "edges" of the idealized PN signal, as received at the

receiver after transmission through the channel TC. Segments of the received

signal, defined by

$$Rc(t;i) = Rc(t) \qquad (t'(i;Rc) \le t \le t''(i;Rc))$$

$$= 0 \qquad \text{(other values of t)}, \qquad\qquad . \qquad (7)$$

can thus be concatenated to form a composite signal

$$Rc(t; \Delta t; comp) = \sum_{k=k1}^{k2} PN(t + \Delta t; k)*Rc(t;i), \qquad (8)$$

where k1 and k2 ($\ge$ k1) are selected integers for the sequence of signal frames

analyzed. The composite signal Rc(t; Δt;comp)) is then subtracted from the

received signal Rc(t) to obtain the remainder signal

$$Rc(t;rem) = Rc(t) - Rc(t; \Delta t; comp), \qquad (9)$$

which explicitly exhibits the effects of multipath on the received signal in each of

the time intervals t''(i;Rc) $\le$ t $\le$ t'(i+1;Rc). From this multipath information, one

can identify the beginning and end of each (time delayed) DFT block and the

corresponding PN sequence, and thus identify a signal frame within a sequence of

signal frames.

After the time delay associated with a received frame is determined or

estimated, signal carrier frequency can be recovered and frequency shift and/or

frequency drift can be estimated, using the known symbol pattern incorporated in

a PN sequence associated with the signal frame.

One or more transmission channel characteristics can be estimated, frame-

by-frame or over a group of frames, using a knowledge of time delay and

frequency shift and/or frequency drift for the frame(s).

In the frequency domain, a signal frame has an associated bandwidth Δf1.

Adequate coverage of this bandwidth without producing an alias signal requires

that the sampling rate in the time domain for a DFT block and for its associated

PN sequence be at least equal to the Nyquist rate. In some instances, this may

require a sampling rate greater than the symbol rate for the signal frame.

The delta function produced by the convolution operation in Eq. (1) has a

very small, but non-zero, temporal width $\Delta t1$, and provision of a signal having

this width in the time domain requires use of a corresponding bandwidth $\Delta f2$ in

the frequency domain. The actual bandwidth $\Delta f1$ provided for the signal frame

should be at least equal to the required bandwidth $\Delta f2$.

One method of estimating one or more transmission channel characteristics

analyzes the Fourier transform $FT(f;Rc)$ of a received signal $Rc(t)$ corresponding

to transmission of an impulse function $h(t)$. Ideally, the Fourier transform

$FT(f;Rc)$ is approximately a sync function,

$$FT(f;Rc;ideal) = \text{sync} (f/f0), \qquad (10)$$

with an appropriate choice of a reference frequency f0 representing bandwidth in

the Fourier domain. The deviation of the actual Fourier transform $FT(f;Rc)$ from

the ideal transform $FT(f;Rc;ideal)$ can be used to estimate one or more (time

varying) characteristics for the transmission channel, frame by frame or over a

sequence of frames, as desired.

Once the time delay associated with a PN sequence (associated with a

signal frame) is determined and compensated for, the PN sequence can be used to

synchronize its associated signal frame.

In any of the formats shown in Figures 2A, 2B and 2C, when time delay

associated with a frame has been determined or estimated, the PN sequence can

serve as a guard interval for the DFT block because (1) the symbol sequence

associated with the PN sequence is known and (2) the beginning time and/or

ending time for the PN sequence is known. Thus, no additional guard interval

within the frame body need be provided. The data payload portion of the frame

body may be increased to include the former guard interval and/or the frame body

length can be reduced by the length of a guard interval that would otherwise be

5   provided in a conventional approach. The information developed in the preceding

also allows demodulation of the received signal.

Insertion and analysis of a PN sequence in each transmitted signal frame

allows the following: (1) recovery of timing, frame by frame if desired, and

estimation of multipath signal degradation; (2) recovery of carrier frequency; (3)

10   estimation of one or more transmission channel parameters; (4) deletion of a

guard interval that serves only as a guard interval; and (5) synchronization of each

signal frame received.

Figure 7 is a flow chart of a procedure for estimating timing of at least one

of the beginning and the end of a transmitted signal segment in the presence of

15   time delay in the signal transmission channel in an OFDM system, according to

the invention. In step 71, a set of K ($\geq$ 1) pseudo-random m-sequences $PN(t;k)$ are

provided that satisfy convolution signal orthogonality, as in Eq. (1) or (5). In step

72, a selected sequence is appended to at least one signal frame to form a padded

signal frame. In step 73, at least one padded signal frame is transmitted through a

20   transmission channel having an uncontrollable signal time delay. In step 74, a

received version $Rc(t)$ of the transmitted signal is received, and a sum

$Rc(t;\Delta t;comp)$ of convolution signals $PN(t + \Delta t;k)*Rc(t;i)$ is formed, as in Eq. (8),

for $k1 \leq k \leq k2$. In step 75, a remainder signal $Rc(t;rem) = Rc(t) - Rc(t;\Delta t;comp)$

is formed,. As in Eq. (9). In step 76, the remainder signal is analyzed to determine

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at least one time at which at least one of the sequences PN(t;k) begins or ends in the received signal Rc(t).

Figure 8 schematically illustrates a transmitter system 80 that can be used to practice the invention. Data are received at a DFT (or FFT) converter block 81 and converted to an appropriate digital format. A PN sequence(s) module 83 provides one or more PN sequences to be used with signal frames containing the DFT information. Output signals from the DFT block 81 and from the PN Sequence(s) block 83 are received at a multiplexer (MUX) 85 and are issued as a MUX output signal containing alternating segments of DFT blocks and PN sequences. The MUX output signal is received and processed by an RF module 87, and the resulting signal is sent to, and transmitted by, an antenna or other signal transmitter 89.

Figure 9 schematically illustrates a receiver system 90 that can be used to practice the invention. A data-carrying (modulated) signal is received at an antenna or other signal receiver 91 and is initially subjected to frequency downconversion by a downconverter module 93. A downconverted signal frame, including a DFT block and an appended PN sequence, is received at a PN sequence processor 95 that performs timing recovery, carrier recovery (optional), channel estimation (optional) and frame synchronization (optional) to provide channel state information. The downconverted signal frame is also received at a PN sequence removal module 97. After the PN sequence processor 95 has performed its task(s), the processor issues a control signal that is received by the PN sequence removal module 97, the appended PN sequence is removed from the signal frame, and the resulting DFT block is sent to a DFT conversion module 99. The converted DFT portion of the original signal frame issues as a demodulated

signal (data). Channel state information obtained from analysis of the PN

sequence issues from the PN sequence processor 95. Optionally, each received

signal frame is analyzed separately to determine the channel state information.